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MODELING OF THE ATMOSPHERIC RESPONSE TO THE LEONID METEOR SHOWERS

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Using data reported from visual meteor counts, we have derived meteor influx rates and size distributions characteristic of the outburst portion of the Leonid meteor stream. We have used these, along with an assumed background flux rate and distribution, in a comprehensive model for atmospheric metals to derive the modifications in the metal layers caused by the Leonid showers of recent years. The model allows for ablation, deposition, diffusion and chemical dynamics, thereby permitting the computation of the modifications in the layers due to the showers in a self-consistent manner, based on observed absolute influx rates. We find that a significant increase in the metal column density is obtained, even from the relatively minor shower of 1996. In the case of neutral potassium, the results are in reasonable agreement with measured column density increases during the shower peak. By scaling the hourly rate of visual meteors to those of the more spectacular showers of, e.g., 1966, we investigate the atmospheric consequences of these major cosmic events.

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1. INTRODUCTION

Meteor showers have been the subject of great fascination throughout human history. In this past century, considerable progress has been made in understanding the origins and periodicities of the major showers. Substantial work has also been directed toward the understanding of the physics of individual meteors as they enter the Earth's atmosphere. What is less well understood at present is the overall impact of meteor showers on the atmosphere. The ablation of meteors in the atmosphere release metallic atoms and ions, including Na, Ca, Mg, K, Fe, and Si. Therefore, the most likely candidates for atmospheric modification are the permanent neutral and ionized metal layers in the mesosphere. Since metal ions are very long-lived in the ionosphere and since transport processes can carry these ions to high altitudes, modification of the ion layers also has implications in the *E*-region and the thermosphere.

Höffner, et al. [1998] have recently reported a substantial increase in potassium column density during the 1996 Leonids, obtained from lidar measurements. Also, *Grebowsky, et al.* [1998] have examined all existing ion mass spectrometry measurements in the *E*-region and have concluded that measurements taken at times of the annual showers show significant increases in metallic ions as compared to non-shower periods. These results indicate that typical meteor showers do have an impact on both the ion and neutral metal layers. These showers, with typical zenith hourly rates (ZHR) of perhaps 10 to 20 visual meteors, would pale in significance to a major meteor "storm" of the magnitude of the 1966 Leonids, where ZHR values of around 150,000 were reported [*Brown, et al.*, 1997]. Any atmospheric effect could potentially be four orders of magnitude larger in this case.

We attempt here realistic simulation of the 1996 Leonids and then to extrapolate that behavior to a major Leonid storm of the 1966 variety. The modeling draws heavily upon the model for meteoric metals in the atmosphere, described fully in *McNeil, et al.* [1988]. It includes a model of the ablation of metals from meteors which is identical to that used by *Love and Brownlee* [1991] except that different metal species are modeled differently in terms of their behavior during ablation. The ablation curve is then injected into a time-dependent code through which the density of the steady state metal layers are computed. The model includes the effects of molecular and eddy diffusion and is spatially one-dimensional in altitude. It includes two components only, neutral and ionized atomic metals, however, a full kinetic scheme for the metals is implemented in this system through the use of steady-state assumptions for the intermediate metal complexes. This approach gives realistic source and sink terms for the metals.

The background deposition, that is, the deposition in the absence of a meteor shower, is computed from a mass distribution derived by *Hughes* [1975]. The background model, which was originally made for sodium, is given revised chemistry and is evaluated at the Kühlungsborn site at the appropriate time. The total influx of background cosmic dust is adjusted to match the climatology recently measured at the site for potassium by *Eska, et*

al. [1998]. In order to apply this to the Leonid meteor shower, a second mass distribution must be derived, which we do from visual meteor data presented by Arlt *et al.* [1997]. The time series describing the influx rates of visual meteors has also been published [*Brown and Arlt*, 1997]. The Leonid outburst mass distribution was scaled up and down as a function of time to represent the added influx during the shower.

The computed increase is then compared to the measured increase, with reasonably favorable results. The model is then rerun under the same conditions, except that the Leonid influx is scaled upwards by comparing the 1996 hourly meteor rate with that reported for the 1966 shower. These results show a proportionate increase in the potassium density which exhibits several interesting characteristics and which has the potential for severe ionospheric modifications when the behavior is extrapolated to more abundant meteoric metals such as magnesium.

2. THE BACKGROUND POTASSIUM LAYER

The first step in the process is to compute the normal potassium layer for the time and place of the measurement. The deposition profile for potassium is computed by assuming a potassium abundance of 0.065% by weight (but this will later be scaled) and a cosmic dust density of 3.2 g/cm^3. As is discussed in McNeil *et al.* [1998] a large portion of the dust population, here 98%, is assumed to have a low geocentric velocity which we take to be 12 km/second. The rest of the population is divided equally with 0.5% at 20, 30, 40 and 50 km/second. The precise distribution of background flux is not critical in this work, since we will not be directly comparing one metal species to another. However, the work cited above shows that this type of distribution, along with the differential ablation hypothesis, will give rise to ion and neutral layers that agree well among the several species tested *and* a depletion of calcium relative to sodium in the mesosphere which agrees well with experimental evidence. The resulting profile for the incoming background K is shown in Figure 1.

Also shown in Figure 1 is the curve after it has been adjusted to give a K column density of 2.5(7) cm^{-2}, which is the result of *Eska, et al.* [1998] for the same region in November. The dust influx is given a diurnal variation according to the diurnal variation in the number of sporadic meteors as measured by radar. Data presented in *Lovell* [1954] was used for this purpose and the total curve was adjusted so that the daily average was unity, that is, so that the average daily influx was equal to that in Figure 1. There is some uncertainty in using meteor radar data for this purpose because small and slow particles are grossly under-represented in the data. The diurnal variation in the column density induced by the variations in influx, using this particular representation, is substantial, perhaps 20%.

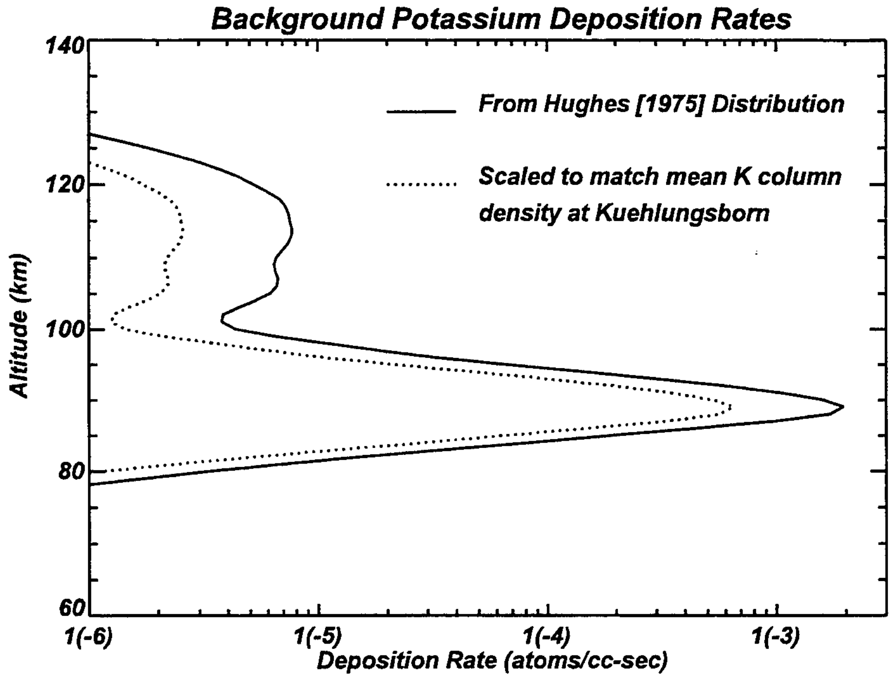

Figure 1. Deposition profile for background potassium computed from the standard Hughes [1997] profile (solid line) and scaled down to match the measured mean column density in November at Kühlungsborn.

The chemistry of the model was also modified to represent potassium rather than sodium. Table 1 shows the rate constants chosen, which come from a variety of sources. The potassium chemistry is not much different from that of sodium, as can be clearly seen. The only rate constant that differs significantly is that for Rxn(1), a sink reaction for neutral potassium and sodium. However, even this is not as significant as it would appear because Rxn(3) is actually the primary sink. The way in which these reactions are transformed into a two-component model including creation and destruction rates for the ions and destruction rates for the neutrals, all strong functions of altitude, is exactly the same as that for sodium, which is presented in *McNeil, et al.* [1998].

The chemical reaction rates with temperature dependence are evaluated at 220° K, which is the approximate mesopause temperature given by MSIS for the site in November and under the prevailing solar/geophysical conditions. The MSIS model evaluated at the site is also used for the major atmospheric constituents O_2, N_2, and O. The minor species are adapted from a variety of sources and are those shown in *McNeil, et al.* [1995]. For the ionosphere, we use the IRI model, also evaluated at the site for November and for the prevailing geophysical conditions. In our model, the ionosphere is fixed and it is assumed that the metals are minor constituents. It is therefore not possible to model correctly the ionospheric perturbation caused by the shower. It can, however, be roughly estimated.

TABLE 1. Kinetics of the Two-Component Models				
#	Reaction	Source	k(Na)	k(K)
1	$M + O_2 + N_2 \rightarrow MO_2 + N_2$	1	4.4×10^{-30}	1.2×10^{-29}
2	$MO_2 + O \rightarrow MO + O_2$	8	7.0×10^{-12}	7.0×10^{-12}
3	$M + O_3 \rightarrow MO + O_2$	1	5.9×10^{-10}	6.7×10^{-10}
4	$MO + O \rightarrow M + O_2$	1,2	2.3×10^{-10}	2.3×10^{-10}
5	$MO + H_2O \rightarrow MOH + OH$	1,2	1.2×10^{-10}	1.2×10^{-10}
6	$MOH + H \rightarrow M + H_2O$	1,2	2.6×10^{-12}	2.6×10^{-12}
7	$MOH + CO_2 + N_2 \rightarrow MHCO_3 + N_2$	1,2	1.9×10^{-28}	1.9×10^{-28}
8	$M + hv \rightarrow M^+$	3	1.7×10^{-5}	2.9×10^{-5}
9	$M + O_2^+ \rightarrow M^+ + O_2$	4,2	2.7×10^{-9}	2.7×10^{-9}
10	$M + NO^+ \rightarrow M^+ + NO$	4,2	2.8×10^{-10}	2.8×10^{-10}
11	$M + O^+ \rightarrow M^+ + O$	5,2	1.0×10^{-11}	1.0×10^{-11}
12	$M^+ + e^- \rightarrow M + hv$	6	4.0×10^{-12}	4.0×10^{-12}
19	$M^+ + N_2 + N_2 \rightarrow M.N_2^+ + N_2$	7,2	2.5×10^{-30}	2.5×10^{-30}
20	$M.N_2^+ + e^- \rightarrow M + N_2 + N_2$	8	3.0×10^{-7}	3.0×10^{-7}

(1) Plane and Helmer's "Laboratory studies of meteoric metals" [1994] all evaluated at 220° K.
(2) Same value used for potassium.
(3) Rates from *Swider* [1969].
(4) Recently measured for sodium by *Levandier, et al.* [1997].
(5) Estimated to be very small from notes by *Rutherford, et al.* [1971].
(6) Values from *Bates and Delgarno* [1962].
(7) Value quoted by *Plane* [*private communication*, 1996].
(8) This rate does not matter in the two-component models used here, since conversion by the reaction is assumed to be complete and immediate.

Eddy and molecular diffusion terms are included in the model. The eddy diffusion coefficient was taken from *Lübken* [1997] and represents measurements taken a few degrees north of the site in winter. The molecular diffusion coefficient used is that for Ar in N_2. The resulting diurnal column density is shown on the left hand side of Figure 2.

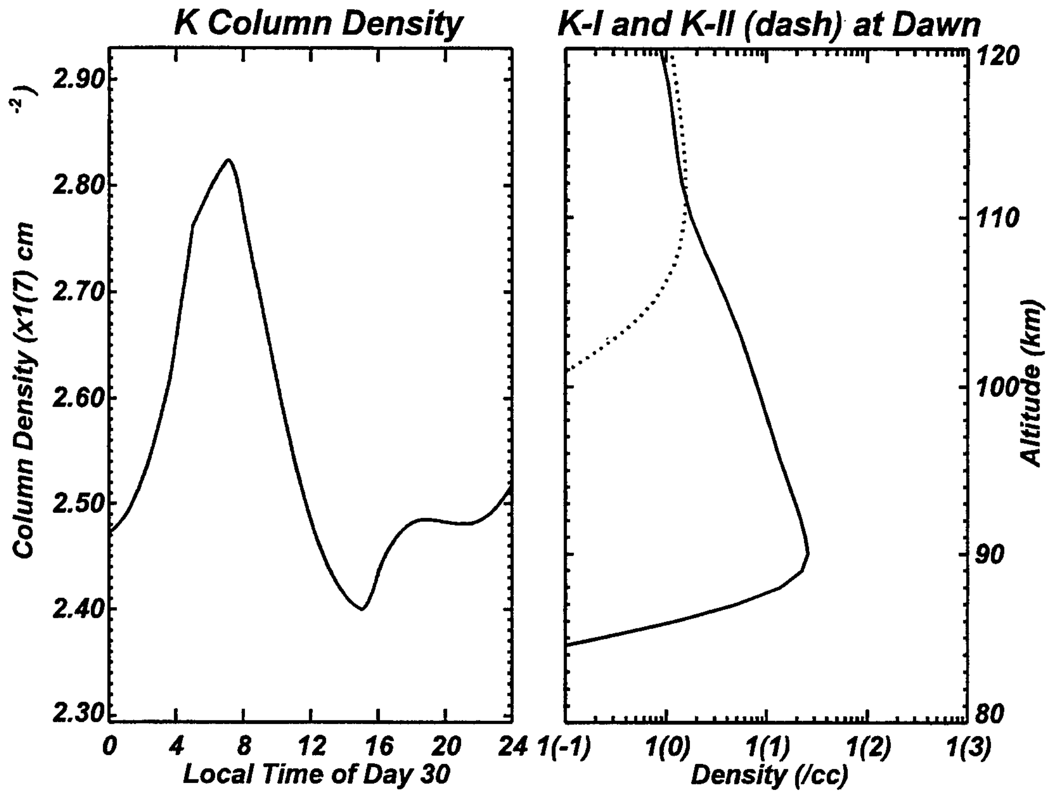

Figure 2. The diurnal variation in the potassium column density modeled for Kühlungsborn on the day of the 1996 Leonids (left) and the neutral and ionized potassium layers at dawn (right).

The right hand figure shows the mesospheric layers at dawn. The neutral layer agrees quite well with the climatology of *Eska, et al.* [1998] who report a November peak density of 20 atoms-cm^{-3} and a peak layer height of 90 km.

3. MODELING OF THE 1996 LEONIDS

The modeling of the shower begins with the computation of a mass distribution. Our method for doing this is outlined in *Höffner, et al.* [1998]. Figure 3 shows the mass distribution compared to the Hughes distribution. The Hughes distribution, shown as the solid line, has been scaled as mentioned previously to give the correct ambient column density of potassium. That scaling is approximately by a factor of three.

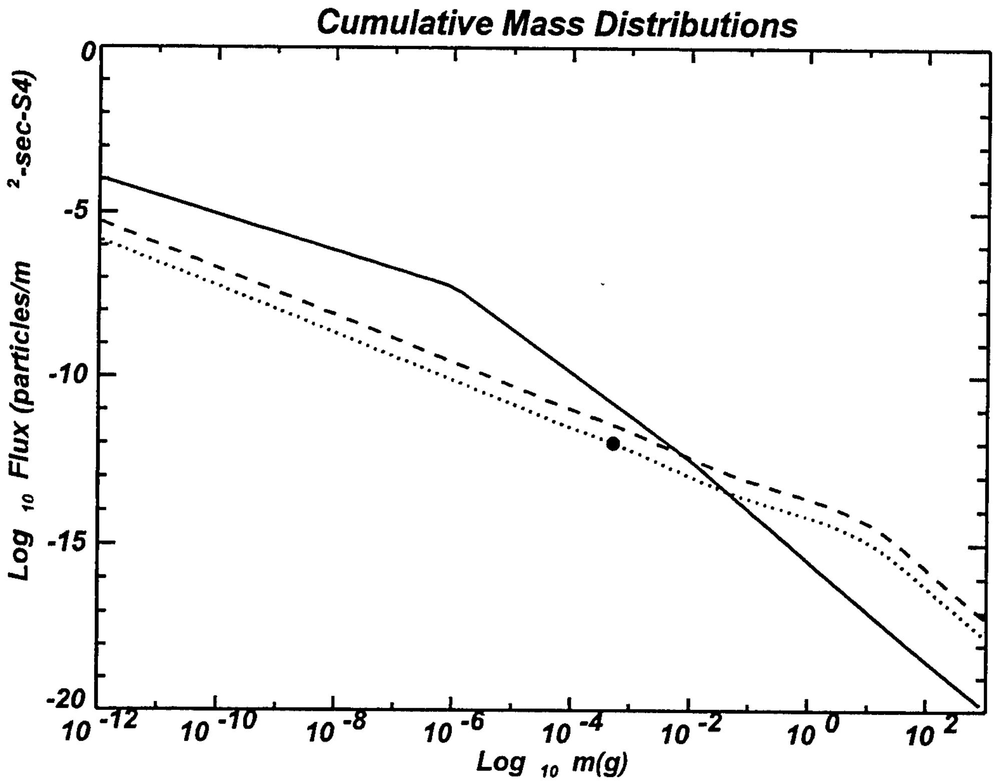

Figure 3. The distribution functions used for the simulation of the 1996 Leonid outburst. The Hughes [1975] distribution (solid line) is used to represent the background influx of dust while the distribution derived from 1996 Leonid magnitude distributions (dashed curve) is scaled up and down in time to correspond to the flux level.

To understand how the Leonid distribution, shown as the dotted and dashed curve, is related to the background distribution, we make reference to Figure 4 which shows the time variation of the Leonid flux at zenith as the solid line. The outburst component is clearly visible between about 0200 and 0700 UT (which is also local time in Kühlungsborn) and the visual data from which the mass distribution is obtained was taken between 0100 and 0500 UT.

The time series data in Figure 4 is quoted to be the flux of all meteors brighter than M = 6.5 and the dotted curve in Figure 3 shows a large circle which is positioned along the x-axis at the point representing M = 6.5 according to the relation of *Öpik* [1954]

$$\log_{10} m = 10.97 - \log_{10} V_g - 0.4M$$

for spongy dust balls. Here, m is the mass in grams, V_g is the geocentric velocity and M is the magnitude. The dot in Figure 3 lies on the 1×10^{-12} particles-m^{-2}-second^{-1} point along the y-axis. Therefore, this represents the case when the flux in Figure 4 reaches 1×10^{-12} particles-m^{-2}-second^{-1}. The dashed curve shows the distribution at maximum, or about 3×10^{-12} particles-m^{-2}-second^{-1}.

If we scale Figure 4 by this value, then we need only multiply the curve in Figure 3 by the scaled time series to represent shower over time. We use the adjusted curve in Figure 4, which is the dashed line. This represents both the reduction in flux due to the fact that the radiant of the shower is below zenith and that the later time measurements are not part of the outburst component. We have ignored the "normal" component of the stream under the assumption that the outburst component is of primary importance. The reduction used for radiant correction was simply the cosine of the angle between zenith and the radiant.

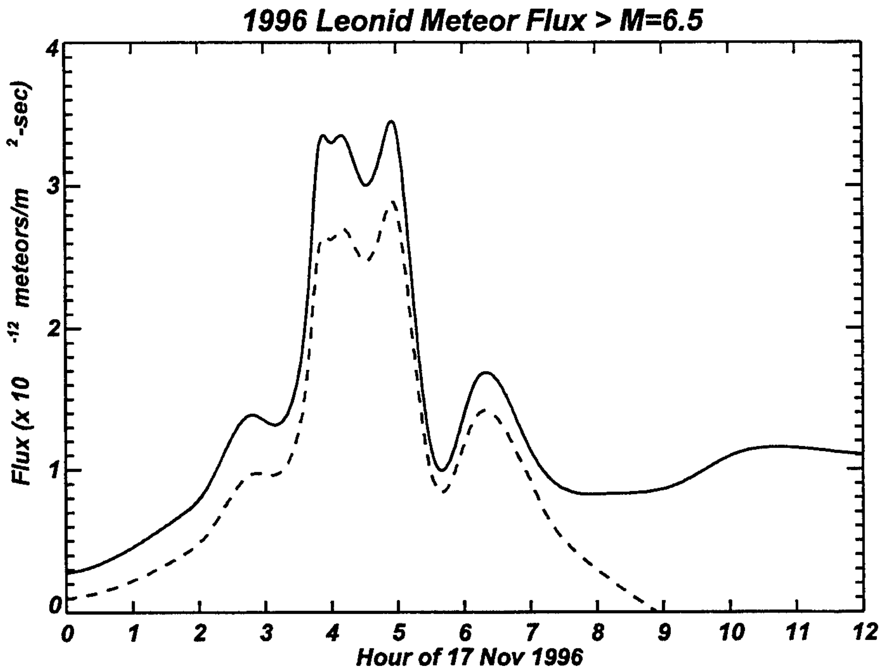

Figure 4. Influx rates for Leonid meteors at zenith (solid line) and at Kühlungsborn (dashed line) assuming that the outburst portion dies out by 0800 L.T.

The deposition function for the Leonid meteors is computed with the same code as was used to generate the background distribution, except that the mass distribution computed for the Leonid outburst is used and the velocity is taken as 71 km/second. The angle of attack is taken to be 35.7° which is the value at 0400 UT. This angle is not varied in time during the simulation. We have found that the effect of attack angle is slight for variation in this range. Figure 5 shows the peak deposition profile of the Leonid stream as the dashed line, compared to the background deposition function. Keep in mind that the absolute magnitude of the Leonid influx distribution is varied in magnitude according to Figure 4 during the simulation while the background deposition is kept constant.

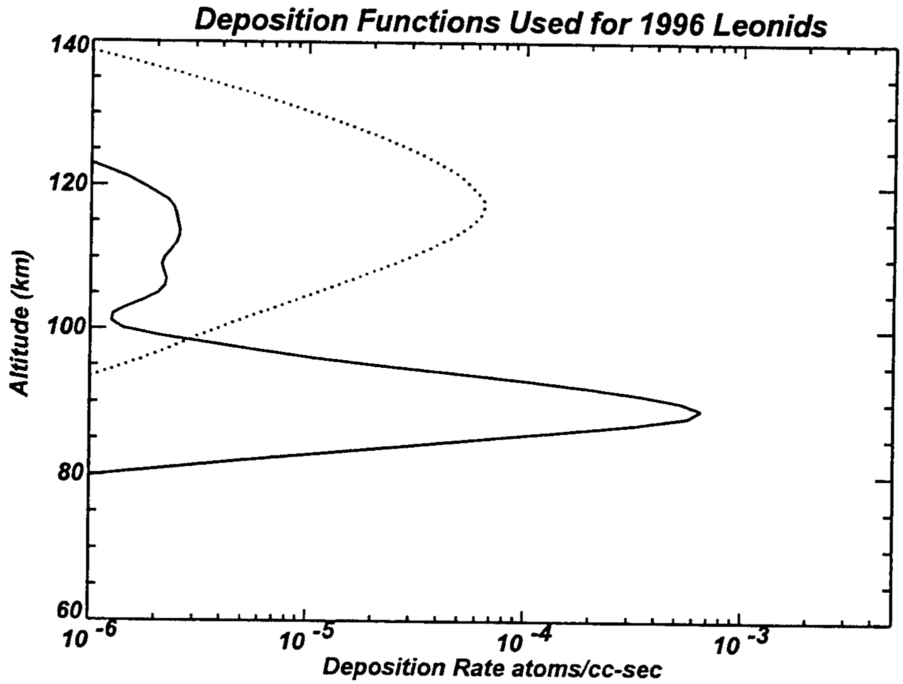

Figure 5. The deposition function for the Leonid outburst component (dashed) line at maximum compared with the background flux component (solid line).

We can see that the peak deposition of the Leonid component is approximately an order of magnitude lower than the peak of the background. It is, however, much broader and therefore could contribute substantial influx. The peak is also much higher due to the high velocity of the Leonid meteors. In the code, the deposition function is not re-computed at each time step. Rather, we have found that it is completely equivalent to simply scale the deposition profile up and down in accordance with Figure 4.

4. RESULTS

Figure 6 shows the resulting change in column density that is obtained with the model. Here, the percent increase is shown relative to the previous day, that is, the normal diurnal fluctuations have been taken out. This will be important when we compare the result to the data. We see that the overabundance increases steadily until about 0500 L.T. then levels off until about 0700 L.T. From there, it begins to decrease. This is not because the metal atoms are going away, but rather because they are being transformed into ions once the E-region builds up and charge exchange rates become large. After about 1600 L.T., that is, sunset, the overabundance begins to increase again, gradually. We have not computed how long the excess atoms stay in the E-region but we suspect that it is at least a few days.

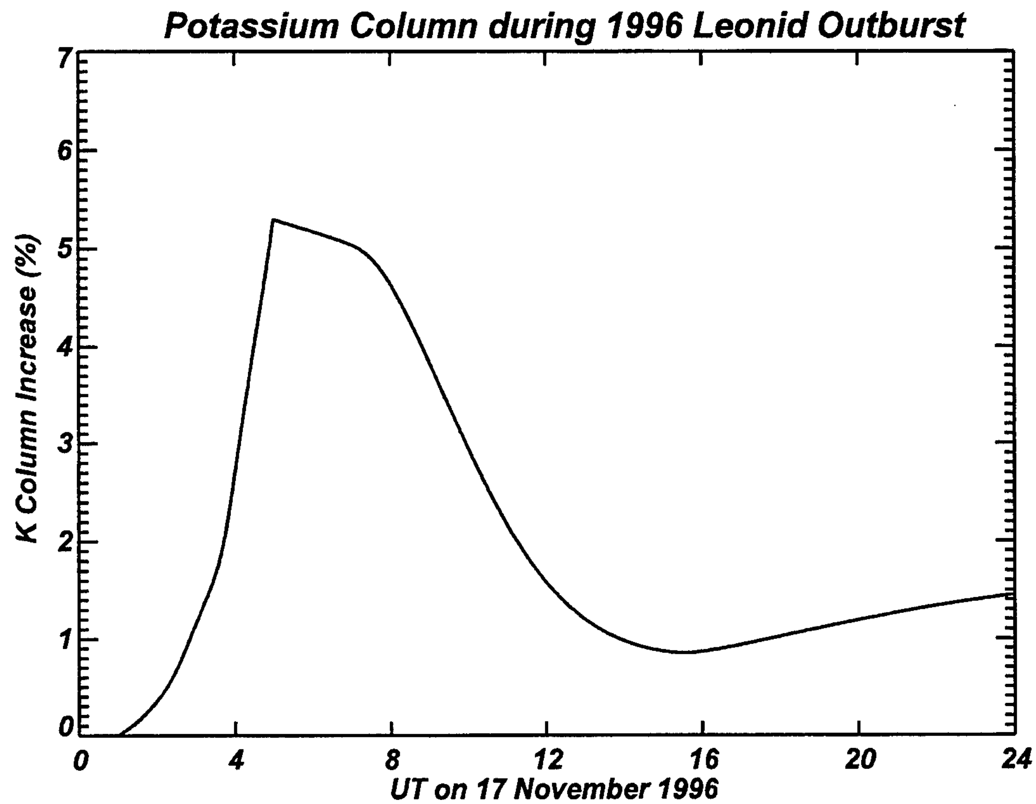

Figure 6. The increase in potassium column density due to the 1996 Leonid outburst which begins at about 0300 UT and ends at about 0530 UT on 17 November.

5. COMPARISON WITH DATA

The simulation predicts an increase in the potassium layer column density of about 5%. Figure 7 shows the column density measured by Höffner and von Zahn during the night of 17 November 1996. The plot shows the deviation of the column density of neutral potassium in percent, compared to the average taken over several nights. The thin lines show the behavior of the layer over several nights surrounding the Leonids. It is evident from these non-Leonid nights that the layer exhibits a relatively high degree of variability from night to night. It is also apparent that there are short-term variations on time scales of an hour or less that change the layer density substantially. These variations in the natural background amount to perhaps as much as 20-30% in column density.

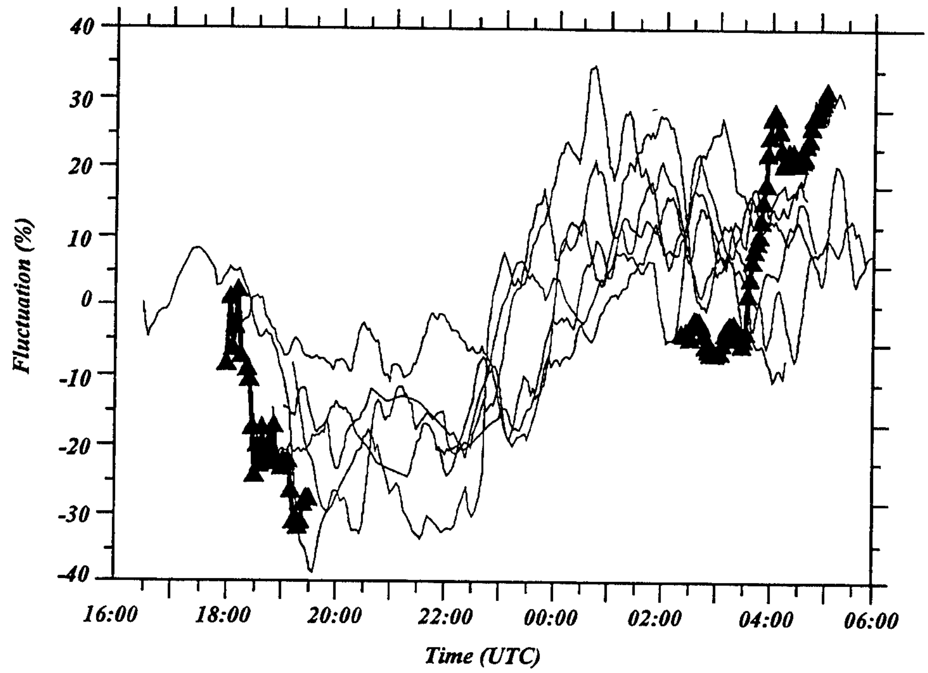

Figure 7. Measurements of the neutral potassium layer carried out by Höffner and von Zahn both during the night of the 1996 Leonids outburst (triangles) and on several surrounding non-Leonid nights. Data are presented as % deviation from overall nightly average.

The measurements taken during the night of the Leonids outburst are represented by the dark triangles. Recall from Figure 4 that the Leonid outburst does not begin in earnest until sometime between 0300 UT and 0400 UT. This is evident from the measured results as well, which are nearly constant at the average background level between 0200 and about 0330 UT. (The measurements were interrupted between 1930 UT the in the evening until 0200 UT in the morning due to cloud cover.) The initial sharp rise in the density which takes place between about 0330 and 0400 UT is most probably due to the presence of several discrete meteor trails in the lidar unit. In fact, *Höffner, et al.* [1998] report several trails which, taken together, encompass this period completely.

After this initial sharp increase, there is a decline by about 10% in the deviation from average density. Following this, there is another increase from 0430 to 0530 UT, when sunrise terminated the measurements. Höffner and von Zahn identify two small trails in this period which might be partially responsible for the increase. However, it is clear that the background layer itself does indeed increase significantly during the outburst.

Referring back to Figure 7, it appears that the most significant part of the density increase takes place between 0300 and 0600 UT, which agrees well with the observations. This means, too, that the better part of the increase was probably captured in the lidar measurements and substantial increase probably did not take place after the

measurements ceased. In comparing the predicted increase of 5% to the data, we should take into account the fact that the measurements in Figure 7 may include some natural variations in the layer, for example, the measured background layer at 0530 UT in Figure 7 is only 20% higher than the non-Leonid levels at this time. Therefore, it appears difficult to derive a precise number for the Leonid-induced increase from Figure 7. It is clear that there was an increase which is probably somewhere between 10%, which is the difference between the measurement at the end the Leonid outburst and the highest value of the column density at a non-Leonid night, and 40% which is the difference in the measured layer *on the night of the Leonids* before and after the outburst. In light of this, and considering the several assumptions involved, this agreement is quite satisfying.

6. MODIFICATIONS IN MAJOR STORMS

With this qualified success, the natural temptation is to try to extrapolate the behavior to the major Leonid storms, the last of which took place in 1996. It is impossible to say how similar the outburst component of the swarm is nearer the center than it is in the portion of the swarm encountered by the Earth in 1996. However, for lack of anything better, we assume the mass distribution is identical. The storm of 1996 has an estimated ZHR of 50 [*Brown and Arlt*, 1997]. The storm of 1966 was reported to have a ZHR in excess of 150,000 [*Brown, et al.*, 1997]. Therefore, it is a simple matter to scale up the influx profile in Figure 4 by a factor of 3000.

Figure 8 shows the relative increase in column density throughout the day, recalling again that the Leonid outburst here took place between 0300 and 0600 UT. The left hand panel of Figure 8 shows an increase in K column of more than two orders of magnitude. The right hand panel shows the ion and neutral K layers. This represents the situation approximately at the end of the outburst. We can see that the neutral potassium layer is no longer anything like expected under normal circumstances, with a rather sharp peak between perhaps 85 and 95 km. Rather, the peak is extremely broad and comes at around 115 km.

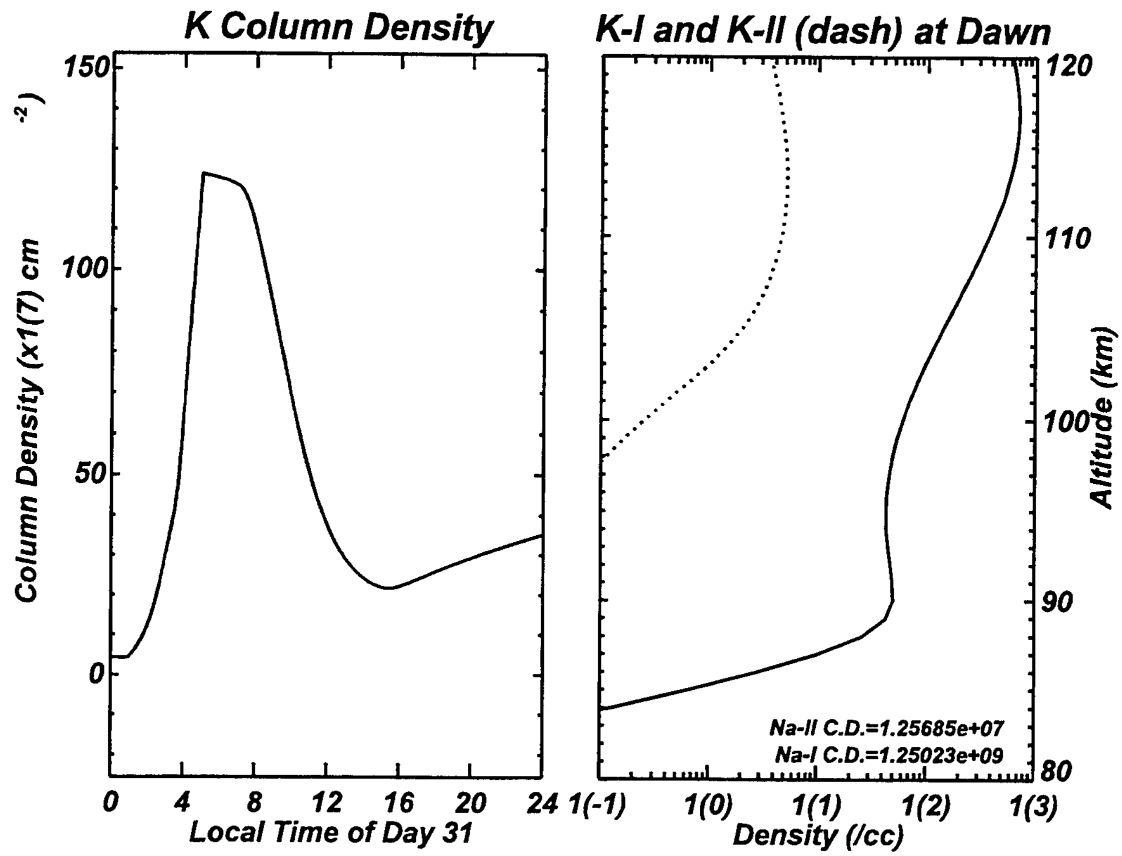

Figure 8. Response of the potassium column density to a shower of the Leonids with maximum ZHR of 150,000 meteors (left) and the K ion and neutral layers at dawn (right).

What is perhaps more interesting is what happens to the potassium during the course of the day. In this model, it is assumed that the potassium is deposited entirely as neutrals. Since there may be substantial ionization of the atomic K at Leonid velocities, this is a lower limit in terms of ion production. We show in Figure 9 the same diurnal variation in neutral K column on the left and the K ion and neutral layers on the right, this time at dusk. Considering only the variation in neutral column, it would appear that the potassium has for the most part gone away. However, the dusk layers on the right show that, instead, the neutrals have been ionized through charge exchange and photo-ionization during the course of the day. They therefore present an ionospheric modification by nightfall.

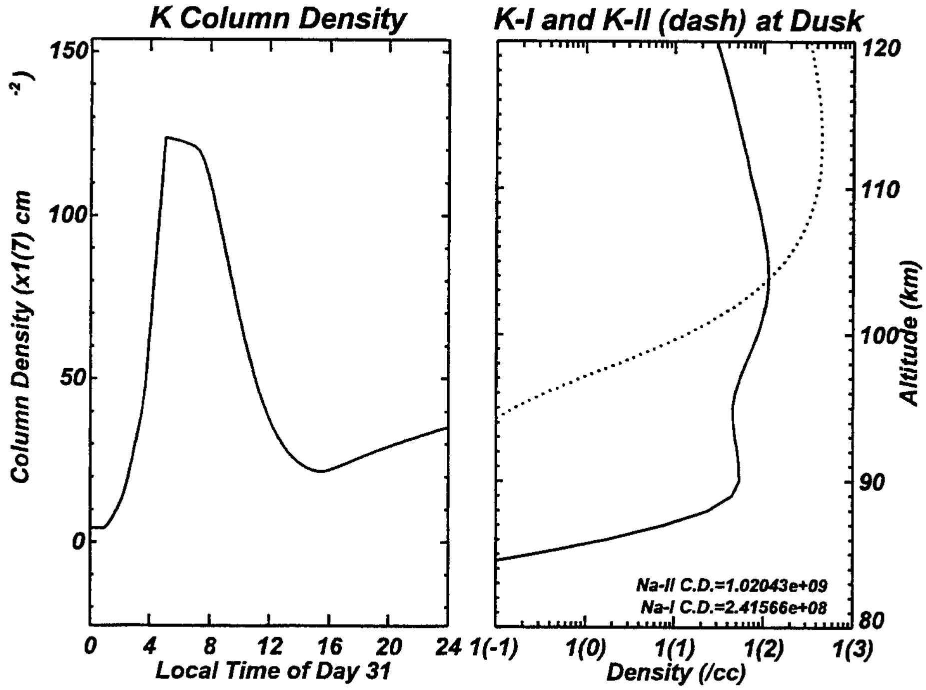

Figure 9. Same but with the ion and neutral layers displayed at local dusk. Charge exchange during the day has built up a substantial K^+ layer exceeding the neutral K layer above about 100 km.

As we mentioned before, it is difficult to accurately assess the ionospheric impact in the present code, since we do not allow for modifications in the natural ionosphere. Charge exchange with metals would necessarily result in a reduction of the *E*-region background ionosphere during the day, which is not represented here. Although these natural species would be replaced to some extent by photo-ionization of ambient NO and O_2, the effect would tend to reduce the rate of ion creation when the density of metals become comparable to the background ionosphere.

We can make some rough estimates of the ionospheric impact of the major meteoric species, at least as an upper limit. One of the most abundant species in meteoric material is magnesium, which is about 400 times more abundant than is potassium. All else being equal, if the potassium layer at nightfall in the 115 km region is 2×10^3 cm^{-3} then the magnesium layer by analogy would be 4×10^5 cm^{-3}. This density certainly rivals the density of the natural ionosphere in the daytime. At night, it would overwhelm the *E*-region background density by two orders of magnitude. We note, too, that these metallic ions would be relatively stable at this altitude and would not recede as does the natural NO^+ and O_2^+ in the region during the night. Therefore, the prediction of the model is for substantial modifications in the ionosphere with the accompanying effects on communications parameters.

7. SUMMARY

We have presented a relatively simplistic simulation of the response of metals in the atmosphere to a low level meteor shower, the Leonids of 1996, and have found reasonable agreement with the measured response in terms of the neutral potassium column density. In a somewhat less precise way, we have attempted to extrapolate this behavior to major Leonid meteor storms. Results indicate that these showers, such as the one in 1966, would cause major perturbations in the metal layers and would give rise to metal ions in the *E*-region with densities equaling or surpassing the background ionosphere, thus causing significant changes to the communications properties of this region.

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